

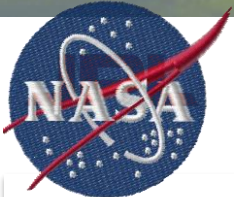
Updates to Force Limited Vibration Testing Handbook (NASA-HDBK-7004C)

Terry Scharton (Consultant) and Ali R. Kolaini (JPL)

Jet Propulsion Laboratory, California Institute of Technology
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Overview

Following are some of the items that will be addressed in the update. Feedback on what users would like to see changed, or included, is requested. (Contact Ali Kolaini at JPL.)

- Moment measurement and limiting
- Limiting peak forces to test limit load (TLL)
- Semi-empirical Formalism (C^2 method)
- Numerical simulation of impedances, forces, and responses
- Notching below test and flight data
- Configurations with manufacturer's preloading hardware
- In-situ calibration procedure and examples
- Force limiting using accelerometer data
- New case histories

Moment Measurement and Limiting

- Sometimes it is necessary to measure and limit the overturning moments during a vibration test, because (like the forces) the moments, in a fixed-base test are often unrealistically large.
- Moment limitations may be associated with the shaker limits, moments in tests at higher-levels-of-assembly, and/or flight limits.
- Therefore, it is recommended that the overturning moments, as well as the reaction forces, be predicted in the pretest FEM analyses.
- Also, because of the complexity of measuring and limiting moments, and uncertainties in establishing moment limits, it is recommended to conduct a preliminary mass simulator test to verify the process, and as a proof test, if the limit is due to the shaker capability.
- As the overturning moments are phase dependent functions of the weighted sum of the forces at the individual transducer locations, the peak values must be determined in the time domain.

Moment Measurement and Limiting (Cont. 1)

The magnitude of the resultant vector instantaneous peak moment $|M_{xy}(n)|$ is determined from the two lateral moments $M_x(n)$ and $M_y(n)$, which include the contributions of both axial and lateral forces, and also the static components M_{x0} and M_{y0} :

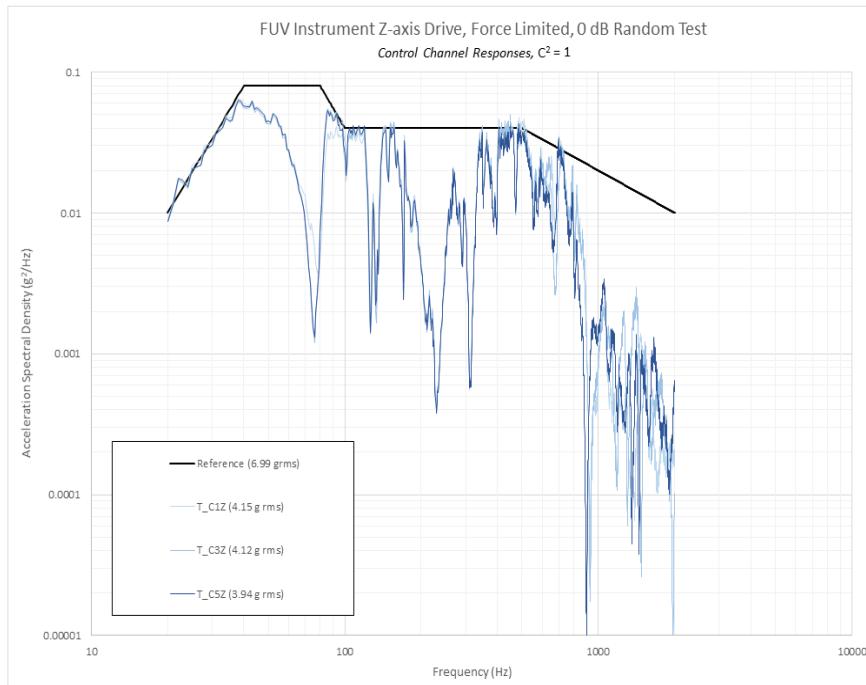
$$|M_{xy}(n)| = \sqrt{(M_x(n) + M_{x0})^2 + (M_y(n) + M_{y0})^2}$$

- In one recent application [1], an iterative statistical approach, using post-processing with Matlab, was used to determine suitable peak factors for estimating the peak moment from the spectral data.
- In another application [2], a virtual controller channel was used to add the various force contributions to the moment in the time domain, and for random excitation, the peak moment was estimated from the spectra of the total moment, assuming a five-sigma peak factor.

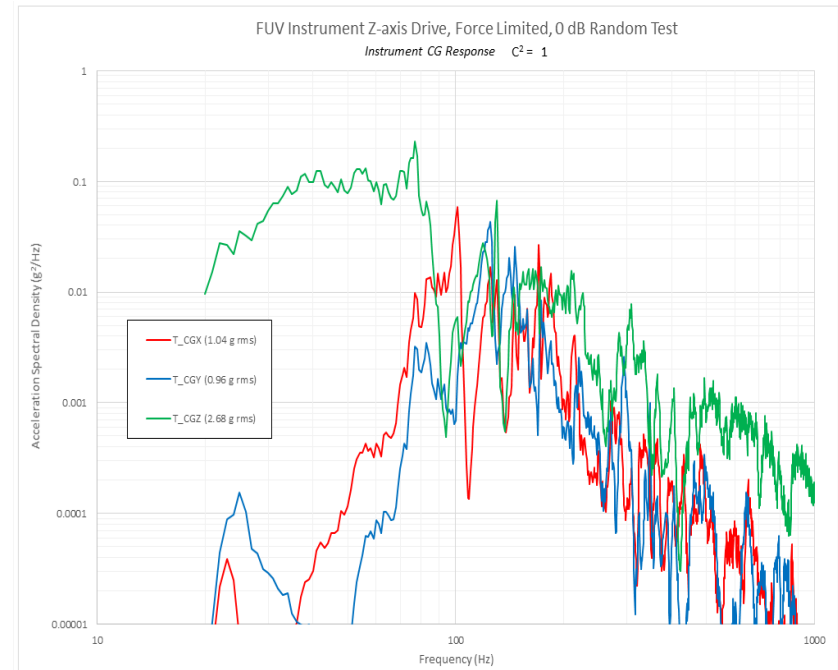
Limiting Peak Forces to Test Limit Load

- Limiting of the peak forces to the test limit load (TLL) can lead to more notching than limiting based on structural impedances, particularly when five sigma peak factors are used.
- Peak factors between 4 and 5 are commonly observed in the measured reaction forces in random vibration tests, and fracture mechanics data indicate that in the frequency range of aerospace random vibration and acoustic tests, failure will occur if the ultimate strength is exceeded. [3,4]
- For the ICON/FUV instrument random vibration test (new case history), impedance considerations dictated a force limit $C^2=5$, but, $C^2=1$ was required to limit the 5-sigma CG acceleration to the TLL, (See next chart.)

Limiting Peak Forces to TLL (Cont.1)



Notching required to keep 5 sigma CG acceleration below TLL, and to keep component responses below that in the previous component-level tests. [2]



5-sigma RSS CG acceleration (total force/mass)
 $(1.04^2 + 0.96^2 + 2.68^2)^{0.5} = 15.2 \text{ G} < 16 \text{ G TLL [2]}$

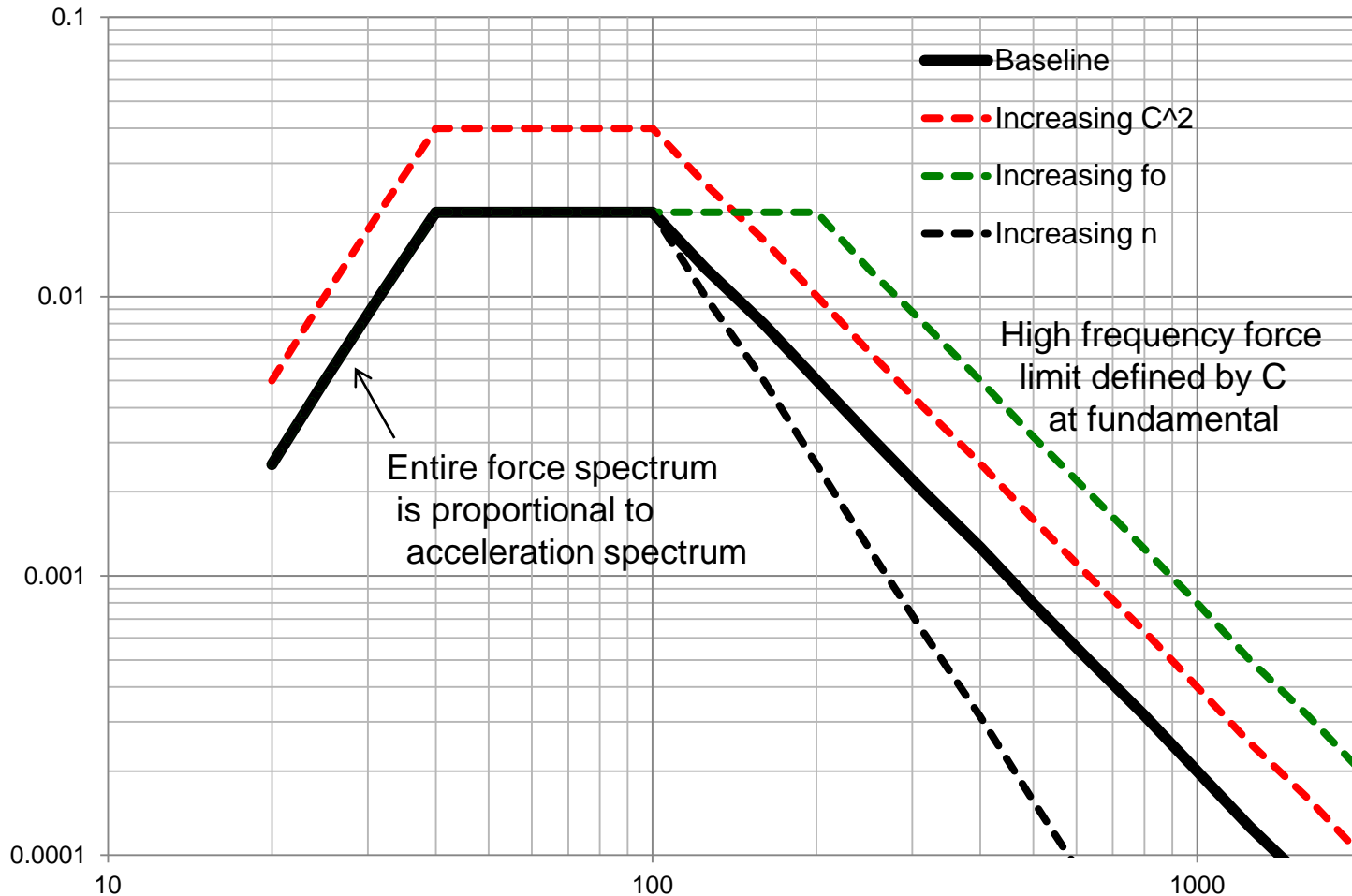
(ICON random vibration tests were primarily workmanship, and low-frequency sine-sweep and loads tests were also conducted.)

The Semi-empirical Formalism (C²)

- The Semi-empirical **Method** will be renamed the Semi-empirical **Formalism** to emphasize that it is more of a format for specifying the force limit, rather than a rationale or justification for the limit.
- In the Semi-empirical Formalism, the factor C simply replaces the amplification factor Q in the equation for the reaction force (F) when a single-degree-of-freedom (SDOF) system with mass (M) is excited at the base with an acceleration (A), e.g., for sinusoidal excitation: $F = C M A$.
- The effects of varying parameters in the Semi-empirical Formalism for random excitation is shown in the next chart.
- In the Semi-empirical Formalism, the force limiting of secondary modes depends on input acceleration, C value, roll-off frequency (f_o), and rate (n).
- The C value is often determined from Fig. 8 of 7004C, where the masses in the ratio $M2/M1$ are the **apparent** masses of the source and load.
- C values may also be determined from numerical (FEM or BEM) analyses or from the heritage of similar test or flight verified systems.

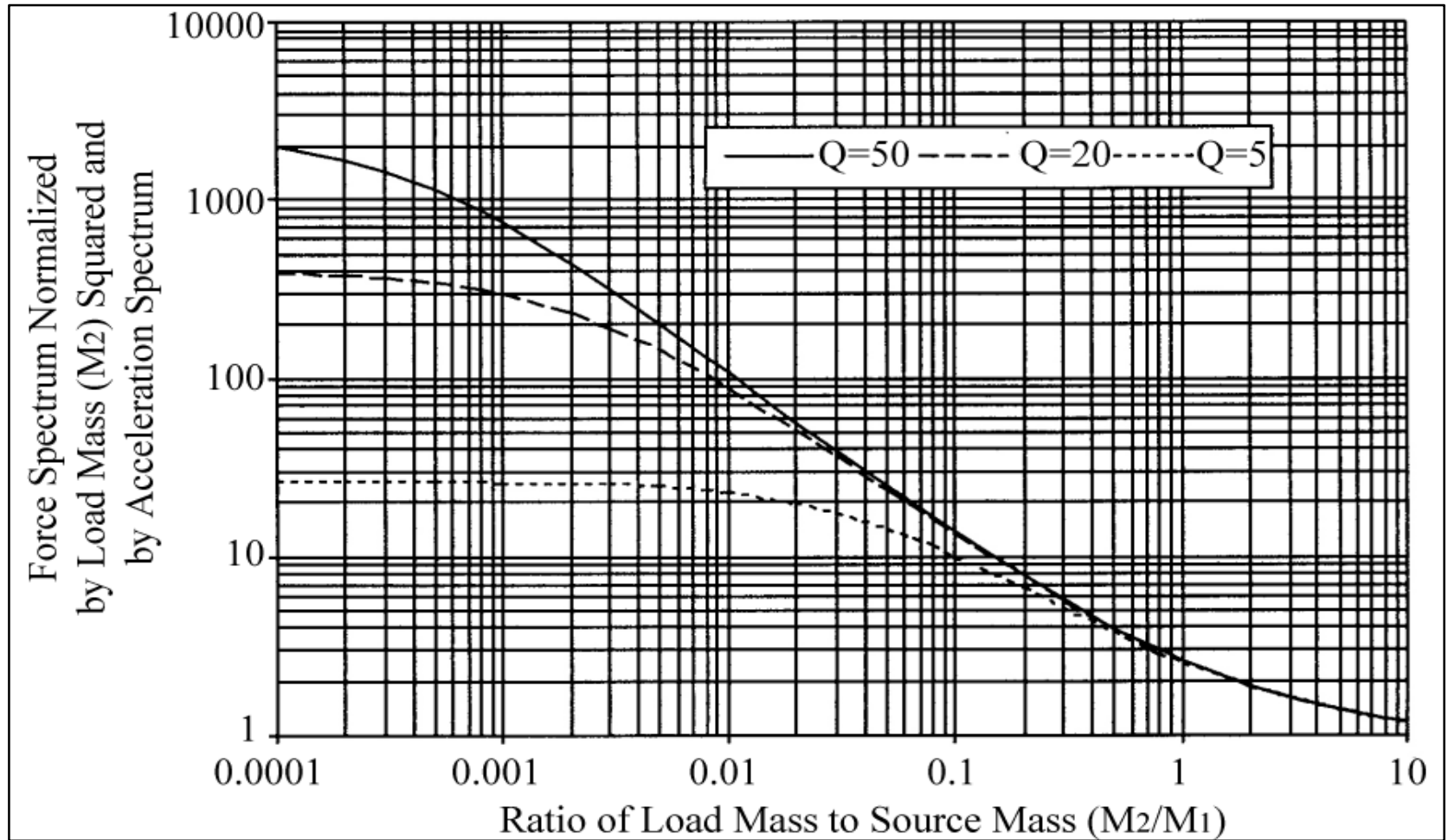
The Semi-empirical Formalism, C^2 (Cont.1)

Semi-empirical Formalism Parameter Variation for Random Excitation, i.e., $S_{FF}(f) = C^2 M_o^2 (f_b/f)^{2n} S_{AA}(f)$, $f \geq f_b$



The Semi-empirical Formalism, C^2 (Cont. 2)

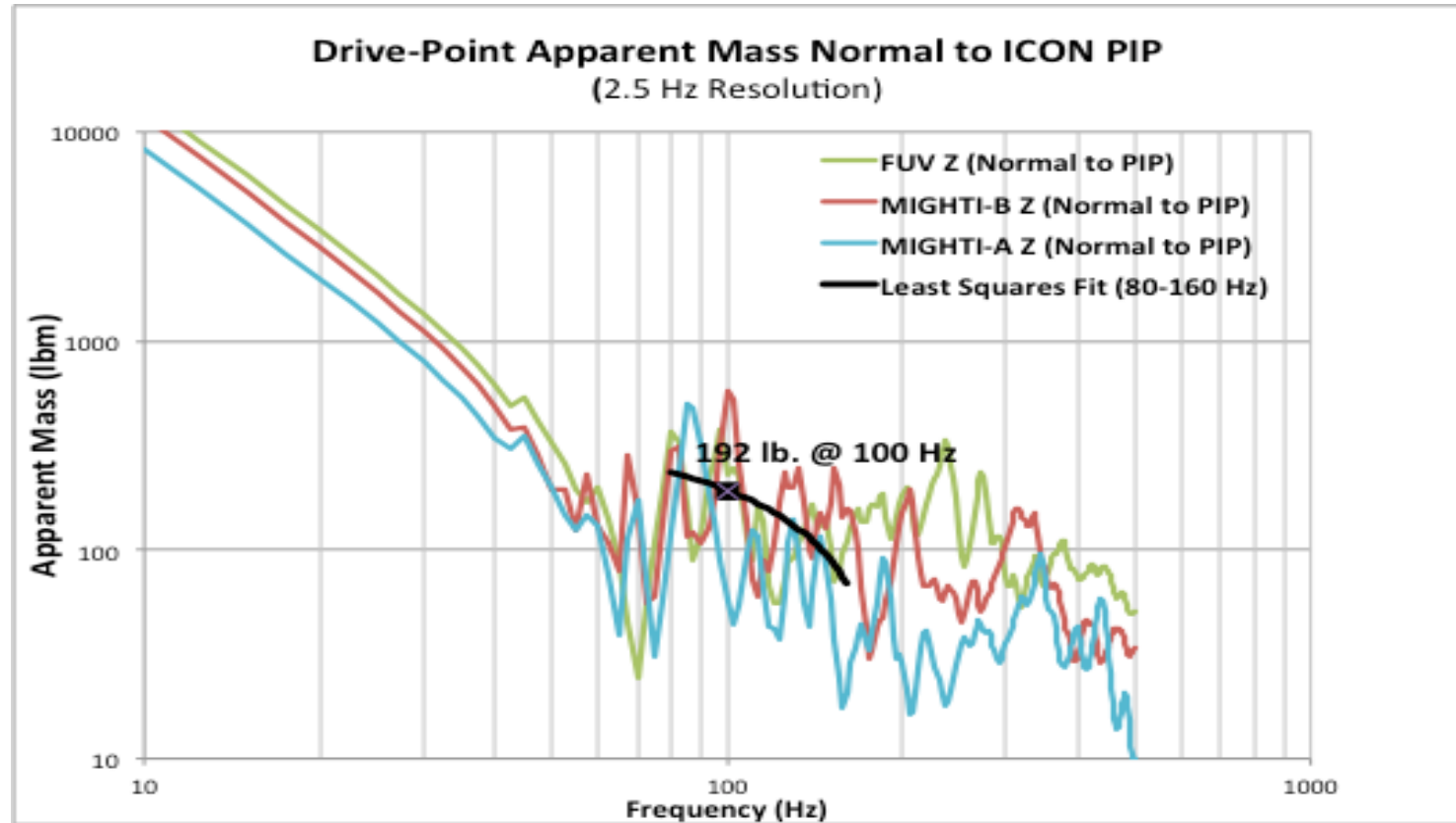
Normalized Force Specification from Simple TDOF System
(Figure 8, NASA HDBK-7004C)



Numerical Simulation of Impedance, Forces and Responses

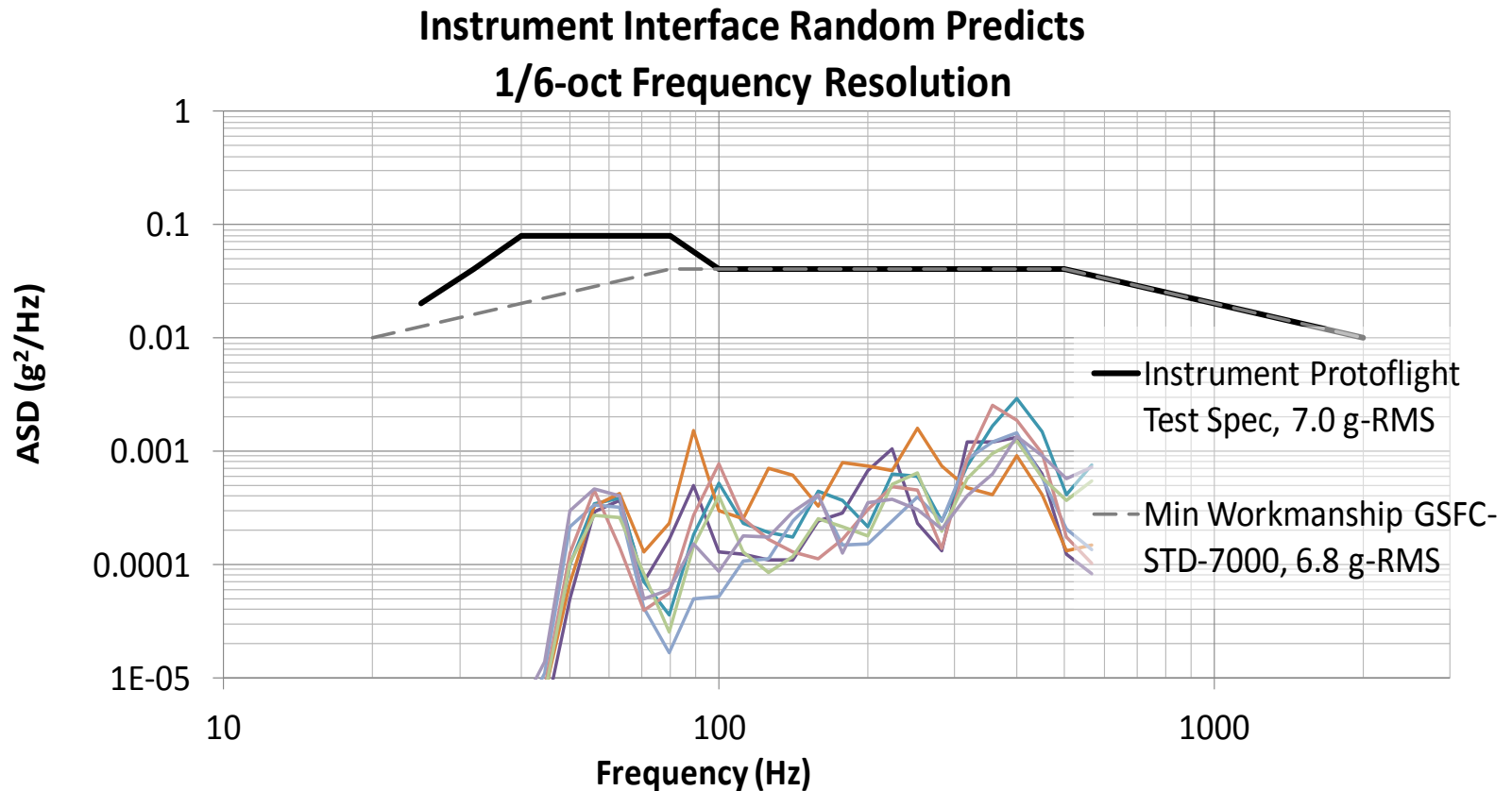
- The Increased capability of computer hardware and software has facilitated the use and value of numerical simulations to support force limited vibration testing.
- The next chart shows a FEM analysis of the impedance of the ICON project payload support plate (PIP).
- The chart 12 shows a BEM analysis of the vibration response of the PIP to acoustic excitation.
- Numerical predictions of the total interface force due to acoustic excitation are problematic and therefore rare, but they would be very useful.

Numerical Simulation of Impedance, Forces, and Responses (Cont. 1)



FEM analysis of the impedance of the ICON project payload support plate (PIP) [5]

Numerical Simulation of Impedance, Forces, and Responses (Cont.2)



BEM analysis of the vibration response
of the PIP to acoustic excitation [5]

Notching Below Test and Flight Data

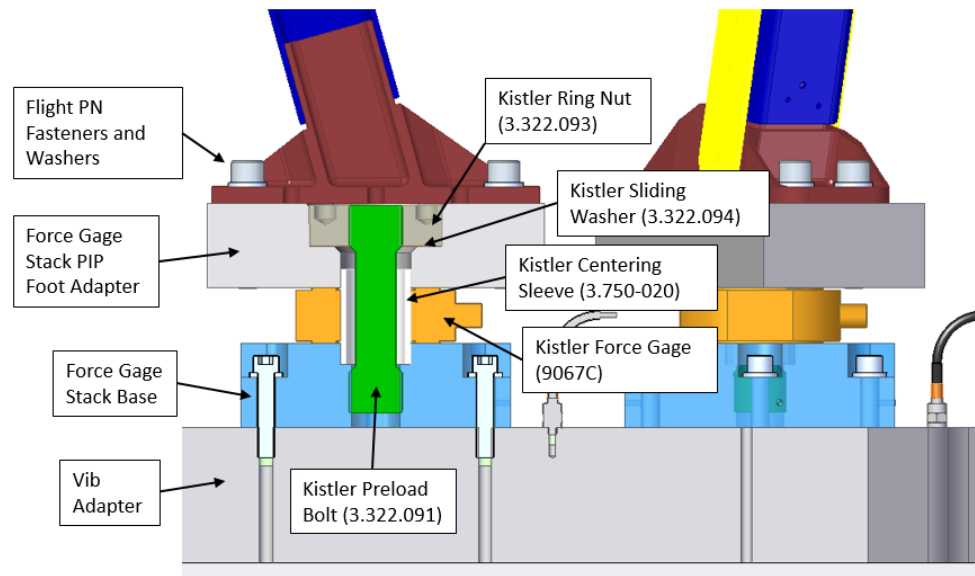
- This is becoming a frequent concern, probably because there is less need for enveloping as FEM simulations, become more accurate, and as more test and flight data are becoming available.
- The basic question that needs to be considered is: “How accurately are the **narrow-band notches** at the payload fixed-base resonances exhibited in the interface vibration spectra predicted in random vibration and acoustic analyses, or in test and flight data?”
- First, the effect of bandwidth. For $1/6^{\text{th}}$ octave-band analyses or data, the ratio of bandwidth to center frequency is 0.12, so that peaks and notches associated with Q 's approximately greater than 8 cannot be resolved; and for $1/3^{\text{rd}}$ octave-band analyses, Q 's greater than 3 can't be resolved. (BEM acoustic analyses are typically narrow-band.)
- Secondly, noise floor, filtering, and sampling rate limitations may obscure notches in test data, and particularly in flight data.

Notching Below Test and Flight Data (Cont. 1)

- Thirdly, the resonances in payload vibration tests often occur at somewhat different frequencies than in analyses or system tests, either because the payload is slightly different, or because the off-axis boundary conditions are different.
- Finally, we should keep in mind that the primary purpose of force limiting is to mitigate some of the artifacts of vibration tests, i.e., the exaggerated responses, different resonance frequencies, and wrong mode shapes, associated with the fixed-base resonances that occur with the test item mounted on a big shaker.
- Therefore, one should certainly take into consideration all available interface analysis or test data, but realize that the narrow-band notches in a justifiable force-limited vibration test may violate these, if the foregoing considerations, or decisions to limit to previous test or capability levels, are applicable.

Force Gage Mounting Configurations Using Manufacturer's Preload Hardware

- Example of using standard preloading hardware for situations where multiple flight fastener mounting is not suited to preloading force gages [2]



(In cases where the flight fasteners lie outside the ring nut, a two-piece force gage foot adapter may be required.)

In-situ Calibration Procedure and Examples

Following are steps and examples for in-situ calibration of force gages [6]:

- 1) Set-up the data acquisition system using the manufacture's calibration value, and note whether their value is for their preload hardware.
- 2) Begin the vibration testing in each axis, with a low-level sine-sweep or random vibration pretest signature test, with the force gages, control accelerometers, and test item in place.
- 3) Compute a "calibration mass" by dividing the measured total in-axis force by the in-axis control acceleration at the lowest frequency where the data are available and reliable.
- 4) If the lowest frequency (f) is above approximately 20% of the fundamental resonance frequency (f_0), correct the calibration mass for the resonance build-up by dividing the measured force by the amplification factor of an undamped single-degree-of-freedom system below the first resonance, i.e., $1/[1-(f/f_0)^2]$. (For a frequency ratio of 20%, the amplification factor is approximately 1.04.)

In-situ Calibration Procedure and Examples (Cont. 1)

5) Compute an “in-situ calibration factor” by dividing the calibration mass by the actual total mass above the force gages, i.e., the mass of the test item and any mounting hardware above the gages

6) If the in-situ calibration factor is significantly different than unity and the difference cannot be explained by the difference between the assumed and actual preloading bolt size or low-frequency amplification, look for possible instrumentation problems, e.g., gage connector mix-ups, bad cables, signal conditioning errors, gage mounting, or local bending.

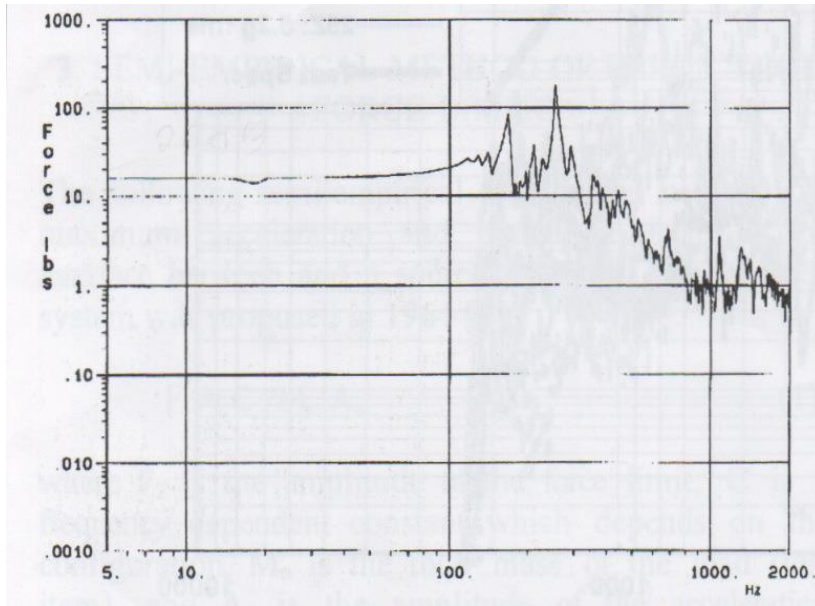
7) After it has been determined that the force gage system is operating properly, use the in-situ calibration factors to adjust the gage sensitivities for the subsequent force limited vibration tests in the subject axis.

Different test labs and test engineers will have different preferences regarding methods of accommodating the in-situ calibration factors.

Options for taking into account the in-situ calibration factors include:

- *changing the gage sensitivities in the charge amplifiers or computer,*
- *scaling the force data in the computer, or*
- *scaling the force limit specification and calculated RMS forces.*

In-situ Calibration Procedure and Examples (Cont. 2)



Case 1 – [6]

Force in 0.25 G test ~15 lb

Calibration mass (force/ acceleration) ~ 60 lb

Instrument actual weight ~ 65 lb

In-situ calibration factor: $\sim 60/65 = \sim 0.92$

Explanation: Bolt shunting

Recommended Action: Multiply the gage sensitivity by in-situ calibration factor of 0.92, to increase the magnitude of the force data in subsequent tests in this axis.

Case 2 – [6]

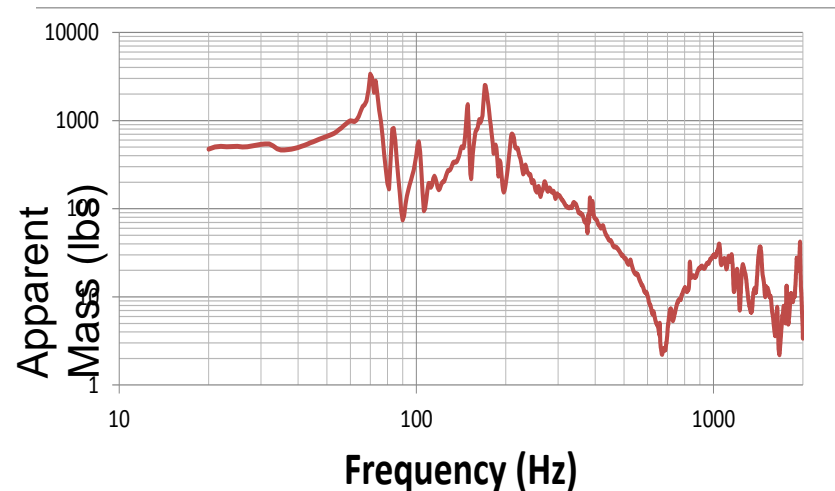
Calibration mass at 20Hz ~ 475 lb

Instrument actual weight ~ 427 lb

In-situ calibration factor: $\sim 475/427 \sim 1.11$

Explanation: Amplification due to first mode at 70 Hz is ~1.09

Recommended action: Don't change sensitivities



Force Limiting Using Accelerometer Data

- Force limited vibration testing requires the use of force gages, or other force measurement instrumentation, to measure the force between the shaker and the test item.
- However, sometimes it is not practical, to employ force gages, but it is desired to take some advantage of force limiting rationale in order to define the notching.
- Herein are summarized a number of techniques, which have been utilized to do some type of force limiting using accelerometer data, but they should be used with caution and the calculated forces and notching discounted.
- All these methods involve limiting the measured acceleration response, and most rely on measuring the Q, which usually requires a zoom analyses.

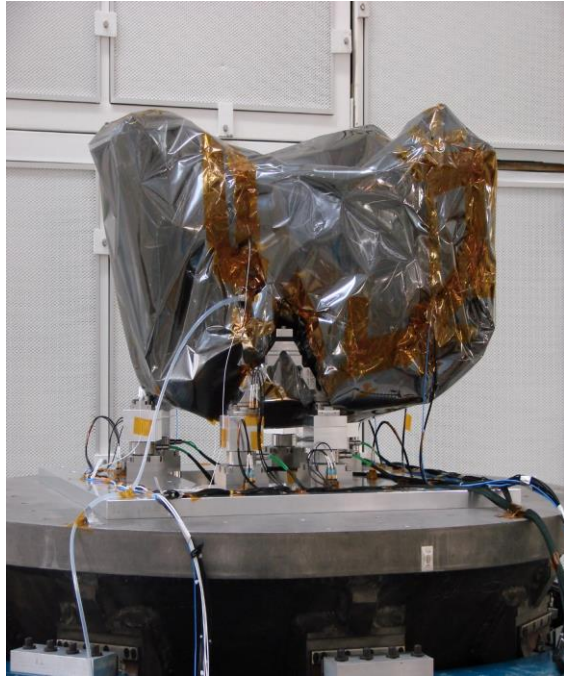
Force Limiting Using Accelerometer Data (Cont.1)

- Sweitzer's Notching Criterion [7]
 - Measure Q , notch by $Q^{0.5}$, so notch depth = remaining peak height
 - Corresponds to picking $C^2 = Q$ in Semi-empirical Formalism
- Knock-down (Notching) Factors
 - Measure Q , and use Simple TDOF Method in Fig. 8 of 7004C
 - Notch by ratio of unloaded to loaded force for given C
- Sum of Weighted Accelerations Technique (SWAT) [8,9]
 - Use least squares to calculate weighting factors from FEM
 - Accuracy depends on accuracy of FEM and on # and positioning of accelerometers
- Use of Effective Mass to Calculate Force [10]
 - Measure Q , and use FEM effective mass and response limiting
 - Accuracy depends of accuracy of Q data and the FEM

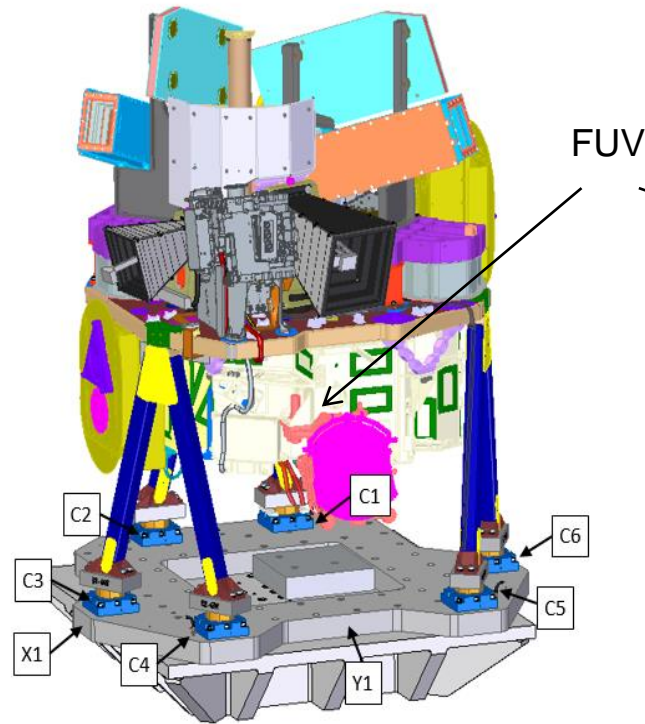
New Case Histories

- Force Limited Vibration Testing of the Ionospheric Connection Explorer (ICON) FUV Instrument at Several Levels-of-Assembly [2]
 - FUV instrument on vertical shaker at CSL (See next chart.)
 - Random, 20 to 100 Hz sine-sweep, and 25 Hz loads vibration testing
 - Random test force limiting with $C^2=1$ to keep RSS CG acceleration below TLL (chart 6)
 - Conclusions:
 - Very accurate pretest analysis
 - 5 sigma and response limits dominated notching
 - Good before/after signature agreement
- Additional Case Histories ???

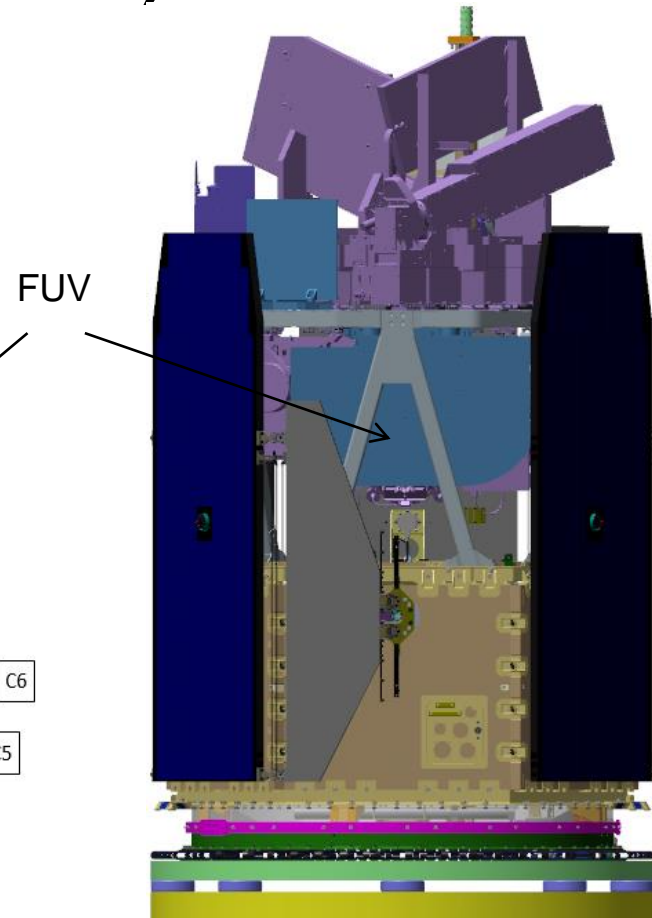
New Case Histories (Cont.1)



Instrument-Level Test



Payload-Level Test



Observatory-Level Test

Vibration Tests of ICON/FUV Instrument at Three Levels-of-Assembly [2]

Summary

- An update of the Force Limited Vibration Testing handbook (NASA-HNBK-7004C) is in progress
- Most topics are revisited and new items include:
 - moment measurement and limiting,
 - limiting peak forces to test limit load,
 - identifying the Semi-empirical Method as a formalism,
 - Notching below test and flight data, and
 - force limiting using accelerometer data
- There will be new case histories, including one in which force limiting was used in tests at all levels-of-assembly (ICON project)
- Your suggestions for other topics to be addressed are solicited ???

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